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VLBI and Precise Space Navigation

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Abstract. VLBI is one of the most powerful methods for precise positioning of spacecrafts. We discuss one of the first experiments of the VLBI application for tracking of the balloons in the atmosphere of Venus — project "VEGA". Another application is the direct positioning of a space radio telescope: the Radioastron mission. A 10-m radio telescope will be launched into orbit to realize the space-ground interferometer. One of the goals of the mission is precise astrometry on the level of several microarcseconds. Possibility of tracking, prediction of the orbital motion of the Radioastron spacecraft is discussed.

1. Measurements of the Venus Atmosphere by Balloons

Progress in space technology and VLBI method [1] have made it possible to implement classical procedures to investigate gas flows into the Venus atmosphere. It was proposed to release free-flying balloons with a transmitter on board into Venus atmosphere [2]. The measurement of the balloon trajectories was carried out by differential VLBI method [3] of relative to the fly-by spacecrafts (VEGA-1 and VEGA-2). In Jun. 1985, two balloons, with transmitters at 1.6 GHz were released from the VEGA fly-by modules. The power radiated in the Earth's direction was about 5 W and distance about 110×10^6 km.

The VLBI method was used here for the first time for a source which moved along an unpredictable trajectory with high and variable acceleration. These circumstances necessitated more complicated algorithms of signal generation and processing and a large number of radio telescopes (radio interferometers) to observe the balloons simultaneously. Twenty radio telescopes, including the largest instruments, were involved. Two 70-m dishes in Ussuriisk and Evpatoriya were finished just before the start of the experiment [4]. Coherent conversion of signals and time-keeping were accomplished with hydrogen frequency standards. The signals were recorded using MK-2 format. On-line Doppler frequency offset measurements were at the largest antennas master stations.

The differential VLBI method is based on the dependence of the phase of interference fringes on the coordinates, and fringe rate on the coordinates and the velocity of motion of source relative to the reference source [5]:

$$\begin{aligned}\Delta\Phi &= A\Delta x + B\Delta y + O(\Delta x^2, \Delta y^2),\\ \Delta f &= C\Delta x + D\Delta y + E\dot{\Delta x} + F\dot{\Delta y} + O(\Delta x^2, \Delta y^2),\end{aligned}$$

where $\Delta x, \Delta y, \dot{\Delta x}, \dot{\Delta y}$ are the relative coordinates and velocities of two close objects (in our case, the balloon and the fly-by module) in the view plane.

The phase measurements provide the highest accuracy $< \lambda/D$. To determine the position unambiguously, a priori data on the source position with an accuracy better than $(\lambda/D) \times L$ (L is the distance to the radio source) are essential. In our case $D = 5000$ km the ambiguity zone is 4 km.

There are several methods to resolve the ambiguity. The first one is the fringe rate differential measurements with the longest baseline and than the phase measurements at interferometers with different baselines. Another method is to determine the delay of the broad band emission signal, accuracy determined by $f/\Delta f$. The synthesis of a frequency is provided by two frequencies spaced at 6.5 MHz. The narrow-band filter was carried for increasing the signal-to-noise ratio. The minimum filter band is determined by stability of a signal oscillator and balloon acceleration and is 1 Hz, the $S/N \approx 10$ (in voltage) at largest (master) antennas (Fig. 1) [6]. We received "frequency legend" for slave radio telescopes. The 0.1 mHz corresponds to 1 m/s. In comparative of these two procedures agreement better than 1 μHz for rate and 1° for the phase was achieved. The fly-by trajectory were measured relatively QSO.

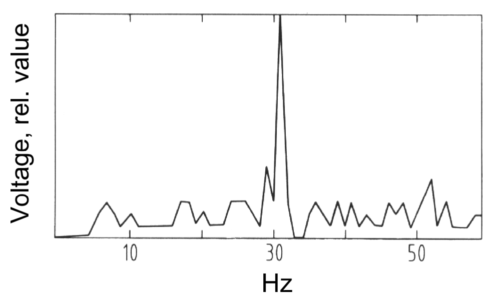

Figure 1. The spectrum of a received signal at Evpatoriya

Balloon-2 launched in the southern hemisphere of the planet led to discovery of gas motion with average velocities of 65.3 m/s and 3.4 m/s in longitude and latitude respectively. Balloon-1, launched in the northern hemisphere, showed that gas motion occur with an average velocity of 68.7 m/s in longitudinal direction, but no wind was detected in the latitudinal direction. The trajectories of the balloons are shown in Fig. 3. The accuracy of phase measurements are 10 km. Balloon-2 drifted from the equator to the North and then moved parallel to the equator. The altitude for the free drift was 53 km.

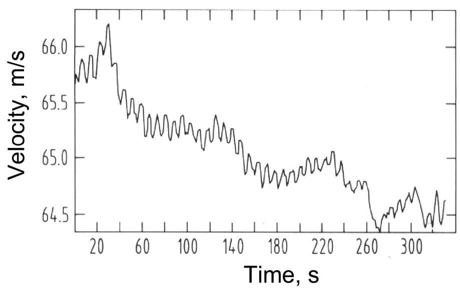

Figure 2. Radial component of velocity of the motion of a transmitter as a function of time

Total visibility times were 34 h and the balloon velocities were $V_1 = 69$ m/s and $V_2 = 67$ m/s.

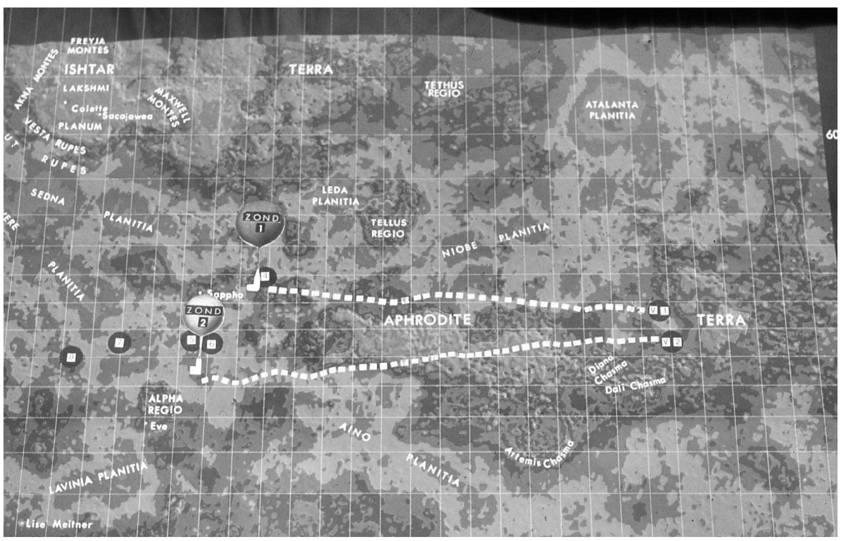

Figure 3. The trajectories of the balloon motions

Variation of frequencies with a period of 7.4 s were detected on many occasions (Fig. 2). These variations occurred more frequently in the southern hemisphere than in the northern one [6]. The peculiarity of balloon-2 determined by trajectory crossing of the Aphrodite mountains. The variability of the signal frequency with 7.4 s period are explanted by pitching of pendulum — the gondola suspended from the balloon by a cord 12 m long.

2. Reconstruction of the Radioastron Orbit Using VLBI Observations

One of the main scientific goals of the Radioastron mission is the study of various astronomical objects with ultra-high angular resolution up to few μas [7]. In order to reach such resolution unstable orbit with high apogee was chosen. Period of satellite rotation around the Earth of about 9.5 days. The perigee radius varies from 10 to 70 thousand km, the apogee radius — from 310 to 390 thousand km.

Accuracy of the reconstructed orbit is determined by the requirements for data processing. Position of the space telescope would be known better than $100 - 300$ m, velocity — 2 mm/s and acceleration 5×10^{-5} mm/s^2.

For more accurate orbit determination the Doppler shift in phase transfer link will be measured by all tracking stations receiving science data stream transmitted from spacecraft.

The goals of simulation were:

- reconstruction of the short orbit arcs (between the thruster's work and spacecraft maneuvers) using Doppler measurements of the radial velocity of spacecraft (RMS error of these measurements is equal to 0.1 mm/s) and;
- reconstruction of the short orbit arcs using VLBI observations of selected radio sources.

Modeling of Doppler measurements of the radial velocity of a spacecraft was calculated for a standard orbit. Then random variations of the coordinates and velocity of this spacecraft, that were in range ± 100 m and ± 1 mm/s, were added. Integrations of the motion equations with Doppler information for many combinations of this noise were made, and comparison with the standard orbit gave us an estimation of accuracy. For one orbital period RMS of position of the spacecraft is less then 3 m, RMS of velocity is < 0.1 mm/s. For short arcs with duration less then < 10 h RMS of position is < 4 cm.

For reconstruction of the short orbit arcs using VLBI observations the NGS-files 95aug22xe, 95aug23xa, 95aug24xa, 95aug25xa, 95aug27xa, 95aug28xa, 95aug29xe, 95aug30xb were selected for modeling. Interval of observation is about period of orbital motion of spacecraft. Radio telescopes GILCREEK, KOKEE, WETTZELL, NRAO85, FORTLEZA, NYALES20, ONSALA60, and WESTFORD worked during period 22-29.08.1995 and HN-VLBA, SC-VLBA, NL-VLBA, ALGOPARK, GGAO7108 during 30.08.1995. It was assumed that after spacecraft maneuvers (1 time per day) 3–5 radio sources were observed. Selected sources are 0804+499 (it was observed more then 10000 times by ground VLBI), 1308+326 (> 40000), 2145+067 (> 35000), 1219+044 (> 8000), 1044+719 (> 15000), 2234+282 (> 35000). The space-ground baseline delays calculated for the standard orbit were corrected (random variations of about 3 ns were added). The clock model for space telescope was unknown and for simplicity it was assumed to be linear function.

Software ARIADNA [8] was used for reduction and analysis of observation. It was shown that observations of radio sources can be used for precise determination of coordinates of the Radioastron spacecraft (< 2 cm); determined position can be used as beginning point for integration of the equations of motion and prediction of orbit.

Simultaneously with orbit determination space-ground VLBI provides high accuracy measurements of coordinates of the selected source. If each of them would be observed 100 times or more during the Radioastron mission we would expect increasing of precision of their position on order of magnitude. The selected sources can be used as fiducial points for new celestial reference frame.

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